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...elopment of Power System Measurements -- Quarterly Report October 1, 1981 to December 31, 1981

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Electronics and Electrical Engineering
Electrosystems Division
Washington, DC 20234

February 1982

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DEVELOPMENT OF POWER SYSTEM MEASUREMENTS -- QUARTERLY REPORT OCTOBER 1, 1981 TO DECEMBER 31, 1981

R.E. Hebner, Editor

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

Foreword

This report is intended to summarize the progress on four technical investigations during the fourth quarter of FY 1981. Although reasonable efforts have been made to ensure the reliability of the data presented, it must be emphasized that this is an interim report, so that further experimentation and analysis may be performed before the conclusions from any of these investigations are formally published. It is therefore possible that some of the observations presented in this report will be modified, expanded, or clarified by our subsequent research.

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October 1, 1981 to December 31, 1981

R. E. Hebner, Editor

This report documents the progress on four technical investigations sponsored by the Department of Energy and performed by the Electrosystems Division, the National Bureau of Standards. The work described covers the period from October 1, 1981 to December 31, 1981. The report emphasized measurements of ion density in air, the use of signals above 1 GHz to detect incipient faults in cables, the measurement of the by-products which develop during partial discharge activity in SF_6, and the determination of the breakdown behavior of an oil-paper interface.

Key words: cables; composite insulation; dc fields; high voltage; incipient fault; insulation; liquid breakdown; SF_6; space charge; transformer oil.

1. INTRODUCTION

Under an interagency agreement between the U.S. Department of Energy and the National Bureau of Standards, the Electrosystems Division, NBS, has been providing technical support for DOE's research on electric energy systems. This support has been concentrated in four areas -- the measurement of electric fields, the measurement of the electromagnetic properties of solid insulating materials and cables, the measurement of partial discharge phenomena in gaseous dielectrics, and the measurement of interfacial electrostatic field distributions and of space charge density. The technical progress made during the quarter October 1, 1981 to December 31, 1981 is summarized in this report.

2. DC FIELDS AND ION MEASUREMENTS
Project No. A018-EES

The objectives of this effort are to investigate devices and measurement techniques which may be used to characterize the electrical environment near high-voltage dc (HVDC) transmission lines, to evaluate methods being used for calibrating such devices, and to develop and establish calibration facilities at NBS which will permit independent verification of the accuracy of user calibrations.

By developing appropriate methods of instrument calibration, it will be possible to compare measurements taken in the vicinity of a high-voltage transmission line with measurements taken in biological exposure facilities. Such a comparison will be necessary in any formal or informal risk assessment.

Most of the technical effort during the reporting period was concerned with preparing reports describing investigations which were completed during FY-81. The titles of these reports and their status are:

"Measurement of Ion Current Density at Ground Level in the Vicinity of High-Voltage DC Transmission Lines," R. H. McKnight, F. R. Kotter, and M. Misakian, NBSIR 81-2410 (published Dec. 1981);

"The Measurement of Net Space Charge Density Using Air Filtration Methods," R. H. McKnight, NBSIR 82-2486 (published Apr. 1982); and

"A Facility to Produce a Volume Containing Space Charge for Use in Evaluating Ion Measuring Instruments," R. H. McKnight and F. R. Kotter (approved for publication).

One project which was completed during the quarter was the evaluation of a measuring system for determining the frequency and magnitude of harmonics in the electric field present in ac biological exposure facilities. These exposure systems, in the simplest form, consist of parallel plates connected to the secondary of a high-voltage transformer. It is important in the biological experiments that the electric field present in the exposure region be well characterized. The electric field can be mapped using a miniature E-field probe such as that developed earlier at NBS. The presence of harmonic components in the field can lead to uncertainty in experiments since capacitively-coupled currents depend on the frequency of the exciting field. Minimizing such harmonics constitutes an important part of the overall "quality control" of the experiment. Harmonics can be enhanced by resonances between the capacitive load presented to the high-voltage power supply by the exposure system and the intrinsic inductance of the power supply itself. The presence of these harmonics must be determined with the system at operating voltage, which may be as high as 60 or 70 kV. Even simple observation of the waveform requires a high-voltage probe and an oscilloscope.

A system which will be used in the field by NBS personnel during evaluations of ac biological exposure facilities has been configured. The system requirements included portability, frequency range up to 1 kHz (to include all harmonics of interest), and overall accuracy of a few percent of the fundamental.

Signals from the exposure system can be derived directly by using voltage dividers, or by the use of capacitively-coupled probes. Because of current limitations in many systems, the voltage dividers would have to be of high impedance to avoid loading effects. In addition, the frequency response of a resistor divider would have to be determined up to the frequency of the highest harmonic of interest. In systems utilizing balanced excitation, two matched dividers would have to be used in a differential scheme.

It was decided to avoid problems associated with voltage divider measurements and to utilize instead a simple capacitive probe. In particular, the output from the miniaturized E-field probe was used as a signal source. This capacitive-coupled mode introduces a minimum perturbation of the system. A schematic of the experimental configuration used to evaluate the filter system described below is shown in figure 1.

A spectrum analysis of the derived signal can be made using several types of equipment: spectrum analyzers, wave analyzers, or tunable filters. Questions of cost and system portability led to the consideration of a battery-operated tunable filter. The filter selected was systematically evaluated in terms of bandpass, shape, gain, and stability. These tests were done using a variety of signal sources.

A theoretical analysis of the system was also made. The results of this investigation indicated that the harmonic content of the electric field could be determined in many cases to an accuracy of a few percent, for the low-lying harmonics of interest ($n<10$). A much more precise system could be designed around a spectrum analyzer. However, such systems are substantially heavier and thus less portable than the tunable filter. The tunable filter is expected to be adequate for identifying malfunctioning biological exposure systems.

The system described above will be used by NBS personnel during evaluation of biological exposure facilities.

Project personnel participated in a field day held at Project UHV in October 1981. This field day was organized by the IEEE Working Group on DC Fields and Ions. Emphasis was on measurement of ion-related quantities such as ion density and vertical current density. Errors associated with measurements of vertical current density made with sensors located above the ground plane were determined for full-scale sensors under the test line. The results of these experiments are consistent with those done in the laboratory at NBS.

For further information, contact Dr. R. H. McKnight, (301) 921-3121.

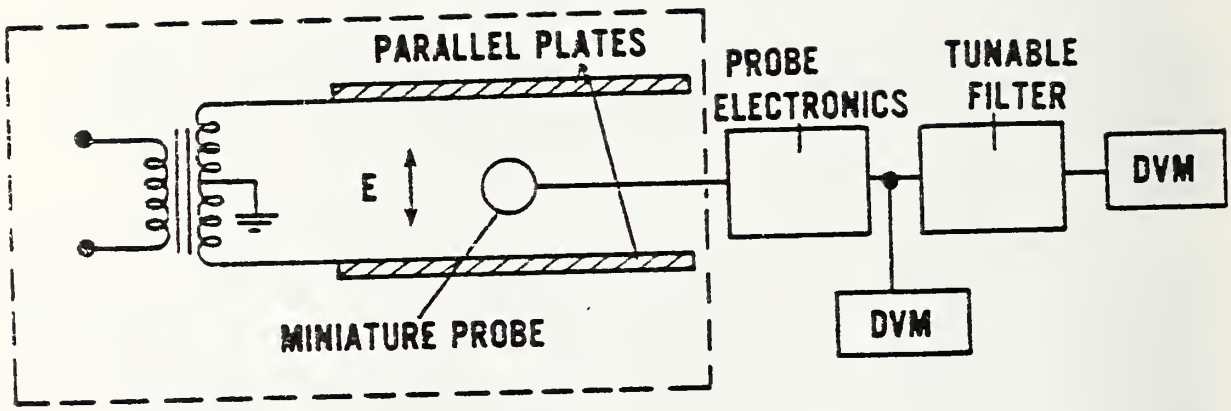

Figure 1. Block diagram of apparatus used to analyze electric field waveforms.

3. INCIPIENT FAULT DETECTION/LOCATION
Project No. A063-EES

The objective of this program is to identify and, insofar as practical, remove technical barriers to the development of a successful incipient fault detector/locator for underground power transmission use. NBS responsibility includes conducting an experimental program that will aid the development of an incipient fault detection/location system by measuring the rf characteristics of power cables, and evaluating the frequency content of partial discharge pulses emanating from incipient fault sites in a cable dielectric.

Previously, attempts had been made to detect incipient fault sites in the cable dielectric using time domain reflectometry (TDR) techniques. This was not successful because of the large attenuation of the TEM wave caused primarily by the semiconducting screening layers of the cable. Some progress had been made with TDR using other waveguide modes with no appreciable electric field in the screening layers. Preliminary measurements suggested successful transmission of some of these modes in polyethylene rods (i.e., no center conductor). The laboratory phase of this program was then terminated before the excitation of these modes in cables was attempted.

In the process of documenting the output of this project and, specifically, preparing a paper for the Waveform Recorder Seminar in Boulder, Colorado in September 1981, a possible measurement problem was noted, which could manifest itself in any experimental setup using discrete sampling. In our case, a time domain function f(t) is sampled at intervals, T, resulting in values:

$$f(T),\ f(2T),\ \cdot\ \cdot\ \cdot,\ f(NT).$$

We then take a Discrete Fourier Transform (DFT) of the sampled function, f(t), in order to obtain the function in the frequency domain:

$$F(\omega) = \sum_{n=-\infty}^{\infty} f(nT)e^{-j\omega nT} \quad (1)$$

This DFT is usually accomplished using Fast Fourier Transform (FFT) or other specialized software [1]. In our case, we sample two time domain functions f(t) and g(t). For example, f(t) might represent the response of a certain length of cable and g(t), a longer length. If in both cases the same connectors and terminations are used, the ratio of $G(\omega)$ to $F(\omega)$ will yield the transfer function of the added length of cable.

In the case of a conventional sampling oscilloscope, we have observed that in practice the sampling rate may drift particularly as the instrumentation is warming up. For ease of discussion we assume

that the sampling interval is constant and equal to T when sampling f(t) and then drifts to a new value T' when sampling g(t). The software, however, expects the sampling interval to be T although the data has been sampled at intervals of T' so that

$$G'(\omega) = \sum_{n=-\infty}^{\infty} g(nT')e^{-j\omega nT}, \qquad (2)$$

where $G'(\omega)$ is the false DFT of g(t). If $T' = \alpha T$ then

$$G'(\omega) = \sum_{n=-\infty}^{\infty} g(nT')e^{-j\omega nT'/\alpha} \qquad (3)$$

$$= G(\omega/\alpha) \ .$$

In other words, a drift in the sampling rate results in a shift in the frequency domain. The problem becomes readily apparent when the ratio $G'(\omega)/F(\omega)$ is evaluated for the case when f(t) and g(t) represent the response of the identical length of cable. If the sampling interval T' is smaller than T ($\alpha<1$), the ratio will indicate high-freqenucy roll off.

We believe that this measurement problem caused by drift is common to all sampling oscilloscopes. Proper experimental procedure could eliminate or at least minimize the effect. A stable time standard could be used to calibrate the oscilloscope's time base during each trace, for example. It should also be possible to eliminate the effects of the drift in software.

This effect is not purely academic in that it has produced an observable modification of our results. The problem is described in a paper presented at the Waveform Recorder Seminar mentioned above, and the theoretical aspects are discussed in a forthcoming paper.

For further information, contact Dr. W. E. Anderson, (301) 921-3121.

4. TECHNICAL ASSISTANCE FOR FUTURE INSULATION SYSTEMS RESEARCH
Project No. A053-EES

The objective of this project is to develop diagnostic techniques to monitor, identify, and predict degradation in future compressed gas electrical insulating systems under normal operating conditions. Focus is on the fundamental information and data needed to improve test design and performance evaluation criteria. The investigation of partial

discharges (corona) in gaseous dielectrics is emphasized. This phenomenon gives rise to degradation of the gas under high electrical stress and may lead to breakdown. Measurement of partial discharge inception in highly nonuniform fields may prove to be a preferred method to determine dielectric strength of electronegative gases.

Planned activities for FY-82 include: 1) complete an archival paper on basic mechanisms of corona inception in SF_6 under ac and dc conditions; 2) investigate the wavelength dependence of photon-induced positive corona inception in SF_6; 3) continue measurements of power dependence of the rates of oxyfluoride and water vapor production from corona discharges in SF_6 and report the results in a conference and an archival paper; 4) explore the feasibility of new methods to measure field enhanced collisional detachment of negative ions in SF_6 and other electronegative gases; 5) improve the accuracy of quantitative analysis of trace gases such as H_2O in SF_6 and other gaseous dielectrics using a gas chromatograph-mass spectrometer, GC/MS, and extend the measurements of the effects of trace H_2O on corona characteristics and relative dielectric strength of the gas; and 6) complete an archival paper on compilation and evaluation of electron swarm data in molecular electronegative gases. In addition, there was an incomplete investigation in FY-81, namely, the measurement of light emission from corona pulses in SF_6 and correlation of results with electrical detection of corona pulses.

Progress was made during the reporting quarter on all of the above activities except activity 2. A paper entitled "Mechanisms for Inception of DC and 60-Hz AC Corona in SF_6" was presented at a special symposium on corona and non-spark discharges which was held during the 1981 IEEE Conference on Electrical Insulation and Dielectric Phenomena. This paper was also submitted for publication in the IEEE Transactions on Electrical Insulation [2], thus completing activity 1 above. A survey of electron swarm data for electronegative gases [3] has been completed and submitted to the Journal of Physical and Chemical Reference Data, indicating thereby the completion of activity 6. As part of activity 3, preparation was begun on a paper giving our results on corona-induced decompositon of SF_6 to be presented at the Third International Symposium on Gaseous Dielectrics. In this report we highlight technical information acquired as a result of activity 5 and measurements of correlation between optical and electrical pulses from corona in SF_6.

Emphasis was given during the past reporting period to performing measurements and tests needed to evaluate the performance and sensitivity of the gas chromatograph-mass spectrometer for quantitative analysis of oxyfluoride content in SF_6. Improvements were made in the data analysis procedure which permit more reliable determination of the absolute concentrations of SOF_2 and SO_2F_2, particularly at levels below 10 ppm by mole fraction. An example of the information obtained is shown in figure 2. Plotted here on a log-log scale is the measured

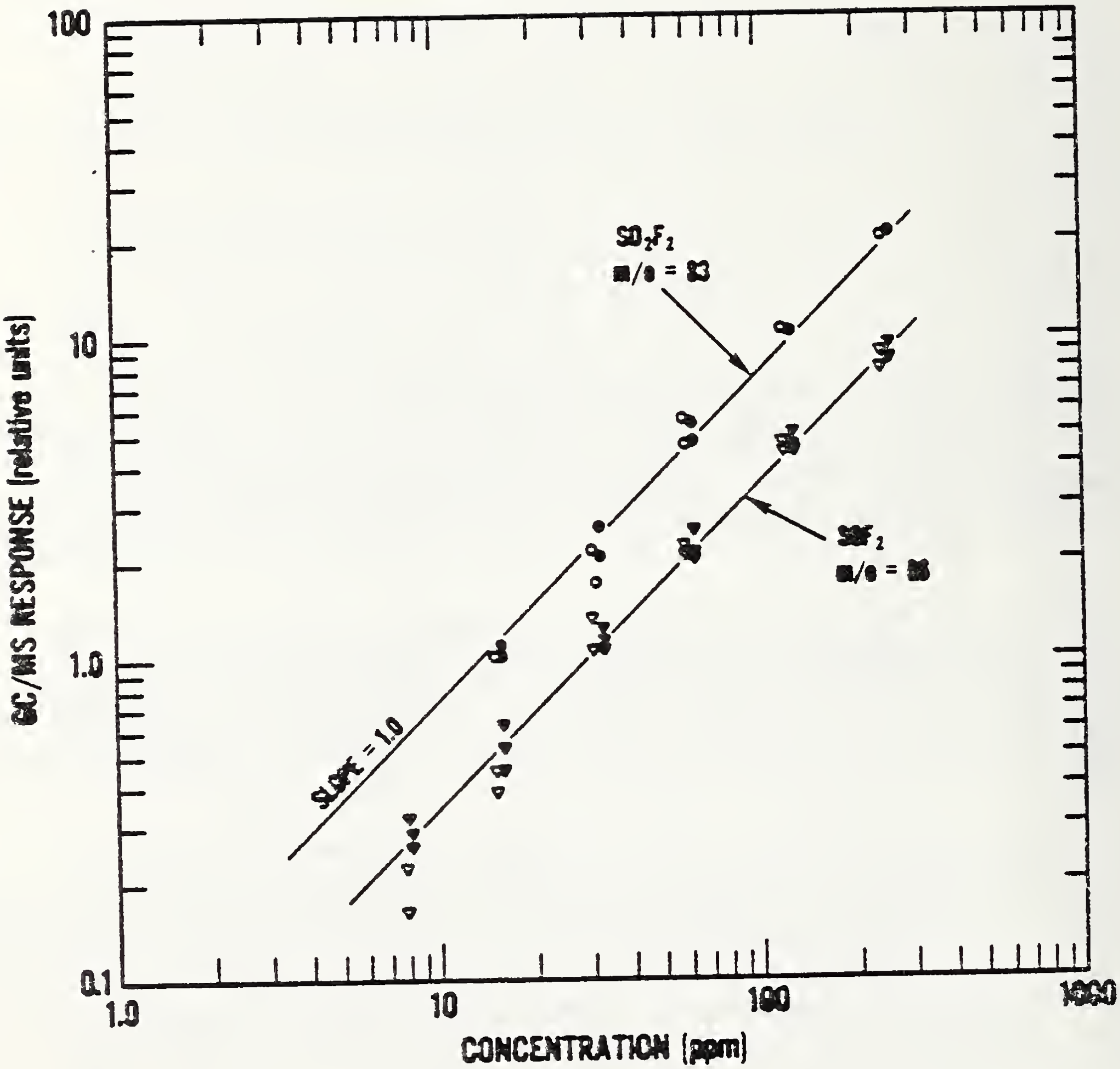

Figure 2. Calibration curves for the gas chromatograph-mass spectrometer. Shown are data for SOF_2 and SO_2F_2 at the indicated mass-to-charge ratios. The open symbols correspond to areas under chromatogram peaks calculated using software provided with the GC/MS. The closed symbols correspond to peak-height determinations.

response from the mass spectrometer output versus concentration of SOF_2 in SF_6 for the ions SOF_2^+ and SO_2F^+ having mass-to-charge ratios, m/e, respectively, in a.m.u. of 86 and 83. These ions give the highest sensitivities for detection of SOF_2 and SO_2F_2. The different symbols correspond to two different methods of data analysis. The open symbols correspond to calculated areas under the peaks in the chromatograms using software provided with the system. The closed symbols are calculated chromatogram peak heights which show less scatter, particularly at lower concentrations, and come closer to fitting a straight line with a slope of 1.0, thereby demonstrating linearity of response. The fact that the response proved to be linear over the range of conditions normally encountered in analysis of SF_6 is significant in that it greatly simplifies the GC/MS calibration procedure.

Reanalysis of chromatograms from our previous experiments on decomposition of SF_6 in corona discharges revealed the presence of SOF_4. This species is postulated to be an intermediary in the product production of SO_2F_2 via the reaction

$$SOF_4 + H_2O \rightarrow SO_2F_2 + 2HF. \qquad (4)$$

The detection of this species has been complicated by the fact that its elution time in the chromatographic column is only slightly longer than that for SO_2F_2. In fact, its presence in the column leads to a broadening of the SO_2F_2 peaks due to the occurrence of reaction (4) in the column. Determination of SO_2F_2 concentrations from calculations of areas under the peaks can lead to serious errors due to overlap with the SOF_4 features. Use of peak heights instead of areas allows considerable reduction in the uncertainties associated with quantitative measurement of SO_2F_2.

It has not been possible to obtain reliable standard samples of SOF_4 in SF_6 for use in calibration of the GC/MS. Thus, an indirect method of calibration for this species has been investigated whereby degraded SF_6 containing SOF_4, H_2O, and SO_2F_2 is analyzed before and after the sample is left undisturbed for an extended period (>8 h). The decrease in SOF_4 concentration due to reaction (4) above corresponds to an increase in SO_2F_2. Therefore, from a calibration using a standard SO_2F_2 sample, together with a determination of the increase in SO_2F_2 from reaction (4), it is possible to make a reasonable estimate of the SOF_4 content.

Further investigations were carried out on correlation between electrical and optical emission pulses from corona discharges in SF_6. The optical emission was detected with a fast photomultiplier tube and the electrical current pulses were detected with a time resolution of ~1 ns. Both signals were recorded simultaneously with a dual beam oscilloscope. The results, as indicated by the oscilloscope traces shown in figure 3, reveal a high degree of correlation in time between

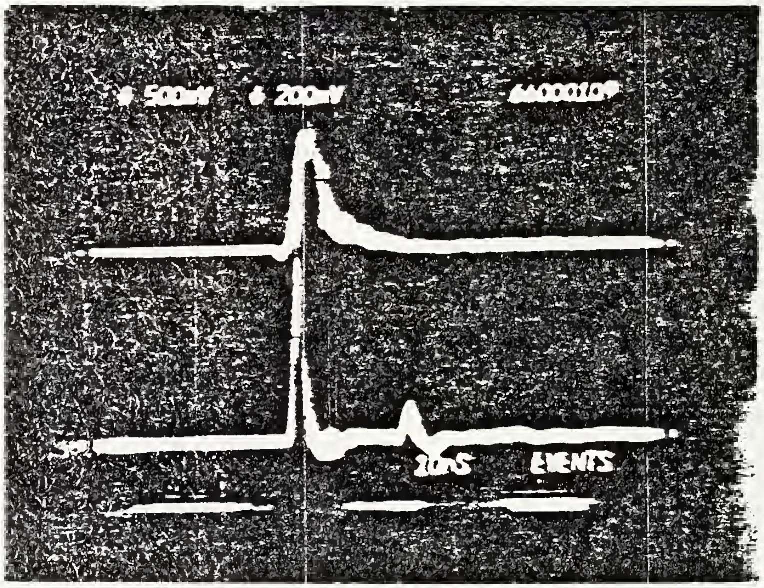

Figure 3. Dual beam oscilloscope traces of simultaneous optical (upper trace) and electrical (lower trace) pulses from positive dc corona in SF_6 at 300 kPa.

the optical and electrical signals. They appear to occur simultaneously to within ±2 ns. This observation is significant because it indicates that the electrical signals can be used as triggers for time resolved measurements of optical pulses and vice versa.

During the next quarter, a conference paper will be prepared for inclusion in the Proceedings of the Third International Symposium on Gaseous Dielectrics to be held in Knoxville, March 7-11, 1982. Some of our recent results on measurement of the power dependence of gaseous by-product production rates from corona in SF_6 will be discussed, together with our observations of correlations between changes in the pulse height distributions of positive corona pulses and buildup of contaminant and decomposition product concentrations. More measurements will be carried out on decomposition of SF_6 in corona. Emphasis will be given to determination of SOF_4 concentrations and the effect which this species has on measurement of SO_2F_2. A technique for continuous calibration of the GC/MS will be set up and tested. Measurements of effects of changing polarity on corona-induced decomposition will also be considered, together with extension of present measurements to higher discharge power levels and other gas mixtures such as SF_6-N_2. Preliminary investigations will be carried out of wavelength dependence of electron avalanche rate in SF_6 for a positive-point-plane gap irradiated with a tunable dye laser or a filtered ultraviolet lamp. The purpose of this study is to determine the minimum photon energy needed to initiate corona via photodetachment of negative ions present in high pressure (>100 kPa) SF_6.

For further information, contact Dr. R. J. Van Brunt, (301) 921-3121.

5. OPTICAL MEASUREMENTS FOR INTERFACIAL CONDUCTION AND BREAKDOWN
Project No. A057-EES

The objective of the project is to develop measurement techniques to determine the interfacial phenomena which influence the electrical breakdown characteristics of composite insulation systems. In particular, the role of space charge in electrical breakdown is being investigated. Specific attention has been placed on performing Kerr-effect, electro-optical measurements of the electric field in transformer oil between parallel plates under a variety of contaminations and at different temperatures. These techniques will then be applied to more complicated transformer oil-pressboard or paper systems.

It is recognized that contamination and space charge may lower the electrical strength of a system. Contaminants such as particles may reduce the breakdown voltage, and space charge may produce field intensifications near one electrode thereby enhancing the probability of breakdown. Past quarterly reports have dealt with the measurement of the electric field in both clean and heavily contaminated transformer oil from room temperature to around 70°C. The contaminated oil of greatest interest was the oil from a failed transformer.

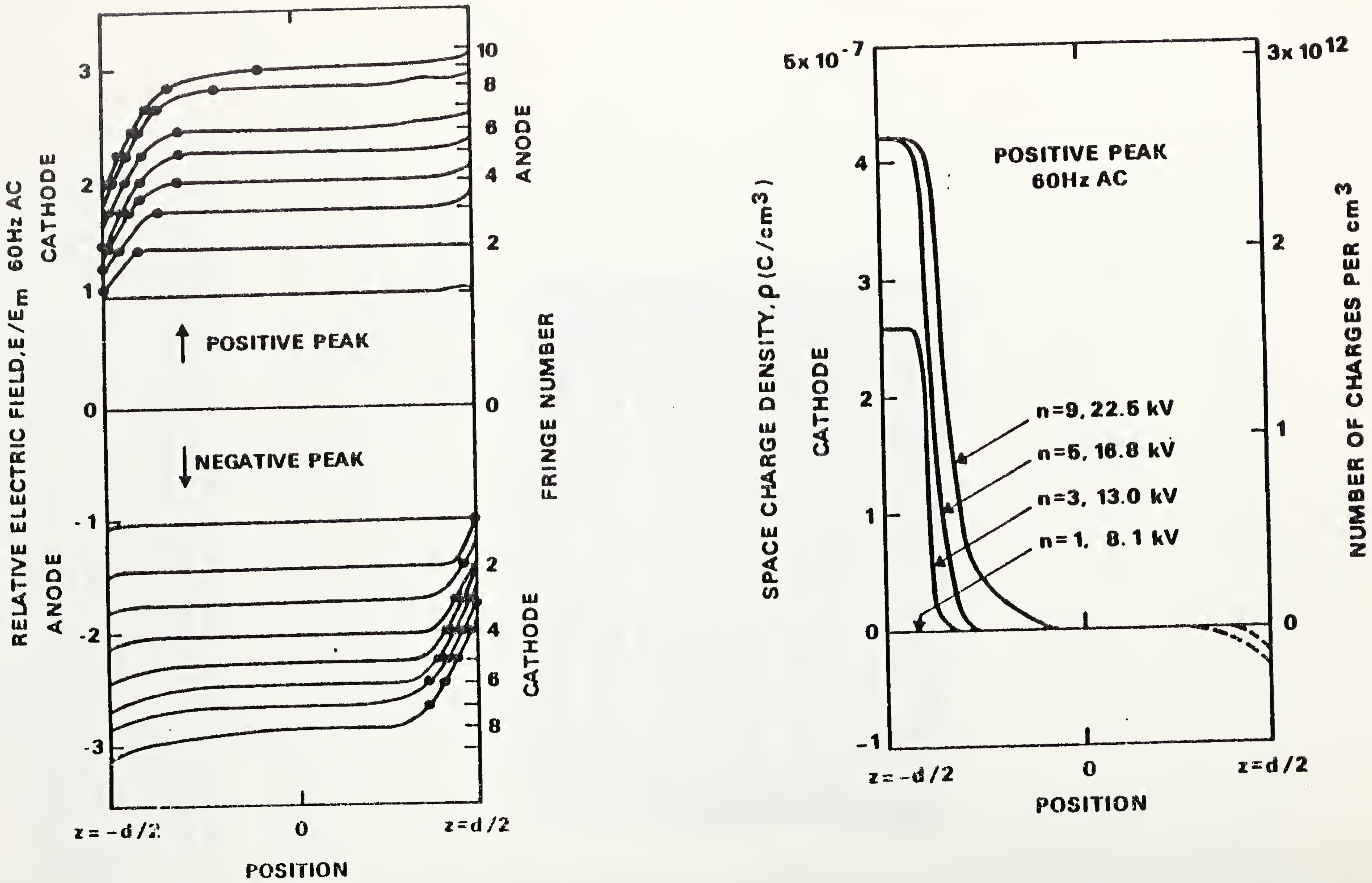

Figure 4. 60-Hz electric field profiles and inferred space charge in nitrobenzene. The field profiles have been inferred from the intensity information obtained from the light measurement system. The fringe number refers to light or dark areas in the Kerr-effect intensity profile.

Previous measurements had shown that, in clean oil, space charge distortion of the uniform field between parallel plates was less than about 5%. It was expected that the contaminated oil might show more space charge, but such was not the case. From room temperature to 68°C, the uniform field was distorted no more than about 6%. It was pointed out at that time that the possibility of systematic thermal optical effects which would produce such an apparent space charge could not be ruled out. Even so, a 6% distortion of the field was an upper bound and was not considered serious in terms of lowering the electric strength of transformer oil by field enhancement. Such a distortion is small compared to space-charge field distortions found in liquids like nitrobenzene.

Earlier in this work, the measurement system's performance was verified by determining the electric field in nitrobenzene between parallel plates. In figure 4, plots are shown which were inferred from the observed Kerr-effect intensity profiles obtained with the measurement system. In this figure Em is the lowest field which would be required to make the Kerr cell transparent. Because the field is not uniform, the amount of space charge present is determined from Poisson's equation $\rho = \varepsilon\, dE/dZ$. It should be noted that the space charge is positive and saturates at the level above 400 nC/cm^3. These measurements demonstrate that the system does respond to field distortions. Since previous transformer oil data suggested the possibility of more space charge as the temperature increased, it became important to further extend these measurements to higher temperatures.

Measurements in clean transformer oil were extended to just above 100°C. In figure 5 plots are shown of the electric field as a function position between parallel plates. These profiles are for the positive peak of a 60-Hz waveform at oil temperatures of 76, 85, 95, and 107°C. Each curve represents an accumulation of the information for 3000 to 4000 cycles of the 60-Hz waveform in order to average out the effects of turbulence. The electric field is normalized to the field's average value. The applied field is on the order of 60 kV/cm with a plate spacing of about 0.6 cm.

Although the 76 and 86°C electric field profiles show an enhancement at the cathode, all the field nonuniformities can be contained with 10% of the field maximum. In the 95°C data there is a sharper apparent field enhancement at the cathode, which is somewhat larger than 10% of the field maximum. It is believed that this apparent enhancement is due to optical effects and not space charge because the same enhancement did not occur with the 107°C profile. It is speculated that there is a systematic effect because of non-equilibrium, misalignment, heating, or a combination of processes, which gives rise to the apparent enhancement so near the plate. This matter will be investigated in the future.

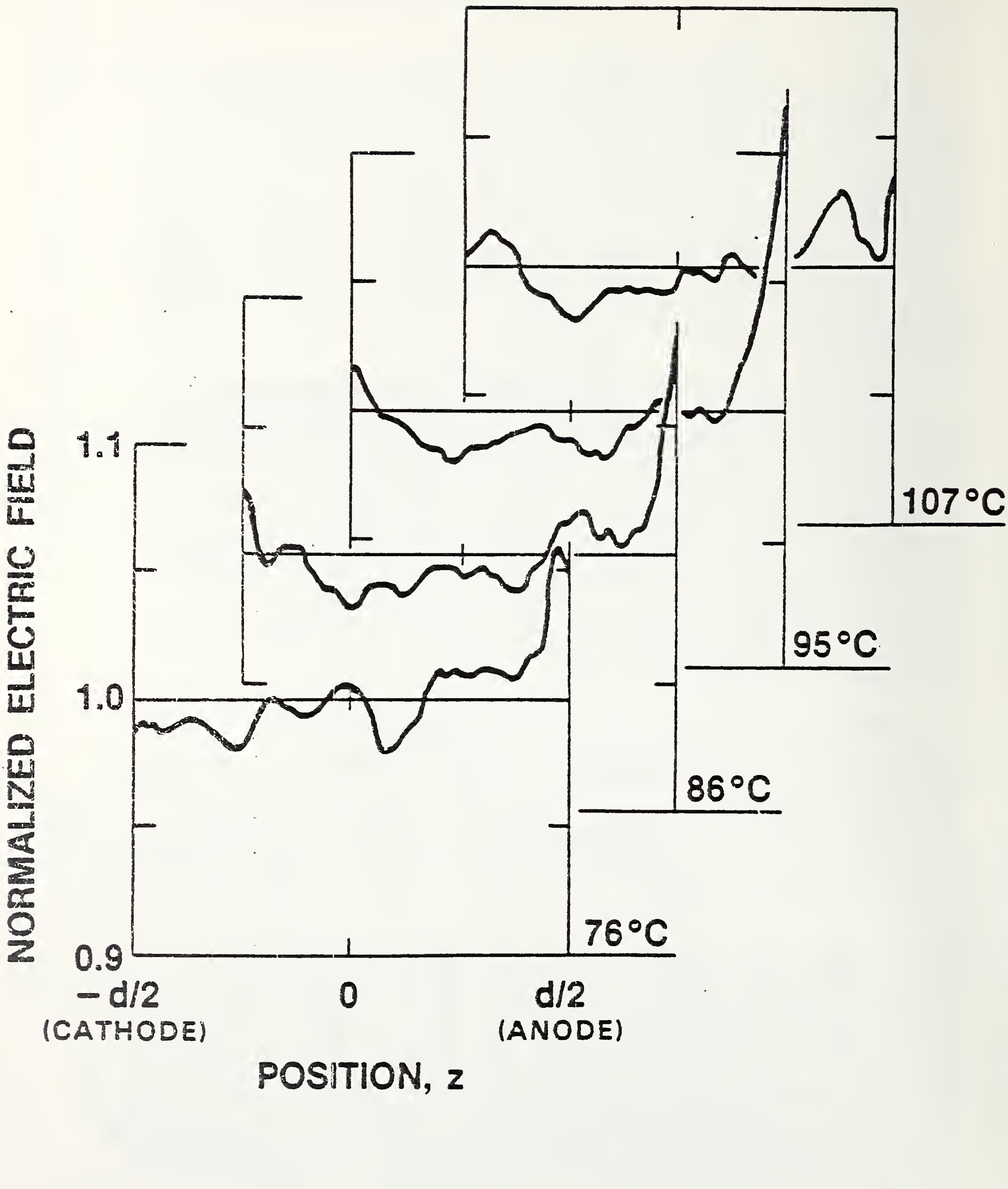

Figure 5. The electric field distributions at four different temperatures in clean oil. Note that the vertical scale in this figure is expanded to accentuate any effects of space charge.

It must be stressed that if the apparent field enhancement persisted throughout all the measurements there would be an objection to ignoring these sharp peaks near the anode. But since it is not observed in the 107°C data it is unlikely that space charge is responsible. If a 10% field distortion were present on the average between the plates this would correspond to a space charge of 2 nC/cm^3.

Although these data did not suggest significant field distortion due to space charge it is not proposed that space charge has no effect in lowering the breakdown strength of transformer oil. The data so far suggest that any space-charge field distortions are small, so that the strength cannot be significantly lowered by field enhancement. It is intended that these measurements will be extended to higher temperatures with controlled levels of contamination in the future. Preparations are also being made to include investigations of the effects of an interface.

For further information, contact Dr. E. F. Kelley, (301) 921-3121.

6. REFERENCES

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This report documents the progress on four technical investigations sponsored by the Department of Energy and performed by the Electrosystems Division, the National Bureau of Standards. The work described covers the period October 1, 1981 to December 31, 1981. The report emphasized measurements of ion density in air, the use of signals above 1GHz to detect incipient faults in cables, the measurement of the by-products which develop during partial discharge activity in SF_6, and the determination of the breakdown behavior of an oil-paper interface.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

cables; composite insulation; dc fields; high voltage; incipient fault; insulation; liquid breakdown; SF_6; space charge; transformer oil.

13. AVAILABILITY

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